

DETECTION SYSTEM FOR NANOMETER SCALE TOPOGRAPHIC
MEASUREMENTS OF REFLECTIVE SURFACES

BY

Henrik K. Nielsen
Lionel Kuhlmann
Mark Nokes

"Express Mail" Receipt No. EL186768033US

Date of Deposit November 18, 1998

I hereby certify that this paper or fee is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231.

Lisa Ralph

Name of Person Mailing

Lisa A. Ralph

Signature of Person Mailing

DETECTION SYSTEM FOR NANOMETER SCALE TOPOGRAPHIC
MEASUREMENTS OF REFLECTIVE SURFACES

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to the art of optical inspection of specimens, such as semiconductor wafers and hard disk surfaces, and more specifically to a system for determining surface topographies in the nanometer range using optical techniques.

Description of the Related Art

Optical inspection techniques for specimens, such as semiconductor wafers, have assessed the relative flatness of specimen surfaces using various techniques. Surface flatness is a critical parameter used to determine the overall quality of a semiconductor wafer, and wafers having large irregular areas or small areas with radical height differences are undesirable.

Current tools available to measure wafer surface flatness include the "Magic Mirror" tool by Hologenix. The "Magic Mirror" operates by directing collimated light toward the wafer surface, wherein the collimated light source is angularly displaced from the wafer surface. The "Magic Mirror" system subsequently receives the reflected light. Light may be scattered toward or away from the detector. The "Magic Mirror" thereupon produces a two dimensional depiction of the surface of the observed semiconductor wafer, with associated light and/or dark areas depending on the type of defect. As can be appreciated, the "Magic Mirror" is a very subjective method of detecting surface contours. With different types of defects producing different optical effects, one cannot say for certain what type or size of defect is responsible for the bright or dark spot or area in the "Magic Mirror" depiction. Hence algorithms cannot

conclusively provide areas of concern or threshold exceedance with reasonable degrees of certainty. The final two dimensional representation obtained from the "Magic Mirror" must be studied by an operator, and results depend on many uncontrollable factors.

An alternate method for measuring surface contours utilizes a profiler, much like a stylus on a record player, which directly contacts the semiconductor wafer surface. Such a system moves the semiconductor wafer and sensor relative to each other causing the sensor to linearly translate across the surface, thereby providing contact between the profiler and the entire surface. Movement of the profiler is recorded, and surface irregularities are detected when the profiler deflects beyond a threshold distance. The problems inherent in a profiler are at least twofold: first, a mechanical profiler contacting the wafer surface may itself produce surface irregularities beyond those present prior to the testing, and second, the time required to make accurate assessments of surface irregularities is extensive. For example, a full map of a single 200 mm wafer using a profiler may take between four and twelve hours.

A system is needed which diminishes the time required to perform surface scanning for contour differences and does not have the drawbacks inherent in previously known systems. In particular, it would be desirable to have a system for determining contours in the nanometer range which would not risk damage to the specimen surface and would be quantitative in nature, thereby allowing for computational determination of surface irregularities using thresholding without ad hoc human review.

It is therefore an object of the current invention to provide a system for determining the contours of the surface of a specimen, such as a semiconductor wafer, in the nanometer

range which can perform surface irregularity determination in less time than systems previously known.

It is a further object of the current invention to provide a system for determining the contours of the surface of the wafer which does not include non-quantitative measurement techniques.

It is a further object of the current invention to provide a system for determining the contours of a wafer surface which does not increase the risk of damaging the wafer surface.

SUMMARY OF THE INVENTION

According to the present invention, there is provided a linear position array detector system which imparts light energy in a substantially normal orientation to a surface of a specimen, such as a semiconductor wafer, receives light energy from the specimen surface and monitors deviation of the retro beam from that expected.

In accordance with the current invention, a laser, such as an argon ion laser, emits a beam toward an optical isolator, which prevents the retro-beam from entering back into the laser, thereby causing laser instability. The beam is thereupon directed through a series of focusing optics and mirrors onto the surface of the specimen. Optionally, the beam may be caused to pass through polarization optics and a birefringent prism, which produces two beams of orthogonal polarization that diverge from each other by a small angle. This angular divergence results in a physical separation of the two beams at the focus of the optical system on the specimen surface, in the same manner as that used in Nomarski differential interference contrast (DIC) microscopy. DIC microscopy is illustrated in U.S. Patent 5,798,829 to Mehdi Vaez-Iravani, entitled "Single Laser Bright Field and Dark

Field System for Detecting Anomalies of a Sample", issued August 25, 1998 and assigned to KLA-Tencor Corporation.

After the split beam contacts the specimen surface, the light scattered at a narrow angle to the incident beam from surface defects is collected in the Dark Field Narrow (DFN) channel, while most of the light scattered at larger angles by the surface defects is collected in the Dark Field Wide (DFW) channel. The remainder of the beam is specularly reflected back through the components outlined above. As two beams illuminate the wafer surface, two beams are returned through the elements up to the birefringent prism, which combines the two retro beams into a single beam. The single beam is returned through the remaining elements.

The retro beam will, with ideal optical alignment, return along the same path as the incident beam if and only if the surface is normal to the beam. The current invention provides a measurement device or sensor within the path of the retro beam to measure deviation of the retro beam from expected. The system uses a diode/detector array, which is preferably a multiple element array of detector-diodes aligned in a linear fashion. The system could be implemented using a CCD sensor or other sensor, but these devices have certain drawbacks. The diode/detector array can be positioned proximate the optical isolator to receive the retro beam, or alternately a polarizing or non-polarizing beamsplitter may be employed in the retro path to divert the retro beam. The beam wander results in the retro beam illuminating different diodes in the array. Weighting the signal from each detector with a weight proportional to the relative position of the beam and adding signals from all detectors in conjunction with a signal normalization using the total detected light power provides a linear voltage proportional to the beam position independent of the absolute light power level.

5 The preferred diode/detector array is made up of 76
adjacent detector elements each having the ability to have
electrical connections at exposed ends of the element. Each
diode has a 280 micrometer length with 30 micrometers between
elements. The entire mechanical dynamic range of the array in
this longest direction is 23.56 millimeters. The width of
these elements is 6.35 millimeters, and thus mechanical
alignment is non-critical for a one millimeter diameter beam.
The beam in the present arrangement, as described in more
10 detail below, is 22 micrometers by 50 or 340 micrometers at
the focal point on the specimen, but 1 mm in diameter at the
detector. It may be appreciated by those of ordinary skill in
the art that diode arrays having different sizing or
composition of elements may be employed while still within the
scope of the current invention.

15 The system measures output from each of the 76 elements
in the array and calculates the center of mass for the entire
arrangement. The relative power of the beam being Gaussian
dictates that the arrays be sized such that the expected
beamwidth spans several array elements. The system operates
20 by scanning the wafer and monitoring movement of the retro
beam from expected.

25 Each diode detector in the 76 element diode/detector
array uses a pre-amplifier. To preserve sensitivity, the pre-
amplifier gain must be relatively high, which is undesirable.
Thus the invention further includes a scheme to increase the
mechanical dynamic range while preserving sensitivity.

30 The signals from each individual diode are summed using a
conventional inverting sum amplifier. Weighting resistors 1
through n provide resistances R , $3 \cdot R$, through $[(2 \cdot n) - 1] \cdot R$,
thereby providing weighting of the signals received from the
sensor array. One summing amplifier is used for each group of
amplifiers, wherein each group has 5 amplifiers and
accordingly 5 array elements. The optimal number of diodes to

be grouped together depends on the laser beam width, diode size, and the gap between the diodes. The system determines the position signal by subtracting the values from two neighbor groups of diodes from one another. A unique stair-stepping arrangement of weightings is employed in the current invention to provide linear response, preserve the dynamic range over the expected path of the retro beam, and prevent saturation of the signal.

Data are selectively passed from the signal groups 1 through n using a multiplexer which receives a digital signal from programmable array logic based on a threshholding arrangement.

This detector as described senses deviations of the specimen surface orientation from normal to the beam along one axis; deviations along the orthogonal axis may be sensed using the optional Nomarski DIC channel by appropriate orientation of the birefringent prism and polarizing optics. Other objects, features, and advantages of the present invention will become more apparent from a consideration of the following detailed description and from the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates the preferred embodiment of the inventive linear position array detector system having a sensor receiving a signal diverted from the input polarizer of the optical isolator;

FIG. 2 is an alternate embodiment of the invention having a sensor receiving a signal diverted from a point within the optical elements using a polarizing or non-polarizing beamsplitter;

FIG. 3 presents a detector array in accordance with the teachings of the present invention having a beam imparted thereon;

FIG. 4 illustrates the relative power of a signal imparted on the diode/detector array of FIG. 3;

FIG. 5 is the diode/pre-amplifier circuit used with each element of the diode/detector array;

FIG. 6 presents the unique weighting/summing scheme and associated amplifier arrangement employed in accordance with the teachings of the current invention;

FIG. 7 shows the weighted summing amplifier, preamplifiers, and diode/detectors used in summing the weighted signals from the 10 centermost diodes in the diode/detector array;

FIG. 8 illustrates the signal from the center group of diodes using the unique weighting scheme of the current invention;

FIG. 9 is a diagram of the stair-stepping dual-weighting arrangement of the current invention, including three summing elements and a position signal selector; and

FIG. 10 presents the programmable logic array and multiplexer arrangement used to determine the output signal of the system.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates the inventive linear position array detector system. The system may be modified from existing technology, such as the existing SP1 system manufactured by KLA-Tencor Corporation of San Jose, California. The SP1 system may include Stationary Beam Illumination technology and an optional Bright Field scanning Nomarski Differential Interference Contrast sensor.

From FIG. 1, a laser 101, such as an argon ion laser operating at a wavelength of 488 nm, emits a laser beam toward an optical isolator 102. The optical isolator comprises an input polarizer 118, a Faraday effect polarization rotator 119, and an output polarizer 120, and operates to rotate the

5 polarization of any beam passing through it by 45 degrees from
its incident polarization. The polarizers are oriented to
pass the outgoing linearly polarized beam from the laser. The
retro beam's polarization will be normal to the pass direction
of input polarizer 118 after passing through the Faraday cell
119, however, and will thereby be attenuated before it enters
the laser cavity and causes instability. The beam is
thereupon directed toward a mirror 103 and down through a half
wave plate 104. The beam may optionally be directed through a
10 polarizing beamsplitter 105, discussed below, and toward a
birefringent, or DIC (differential interference contrast),
prism 106. The DIC prism 106 operates to split the incoming
linearly polarized beam into two separate beams of orthogonal
linear polarization that diverge from each other by a small
angle. These two beams then pass through an optics
arrangement 107, which comprises a series of lenses used to
focus the beams toward the wafer surface. The focused beams
are directed to second mirror element 108, which directs the
beam toward third mirror element 109 and onto the surface of
the wafer 110. As shown herein, the beam is stationary as
opposed to scanning beams used in other known optical
inspection devices.

25 ~~The optics arrangement 107 includes first lens 111, mask
112, second lens 113, third lens 116, and fourth and fifth
lens combination 115, comprising fourth lens 115a and fifth
lens 115b. These lenses in the optics arrangement 107 shape
and focus the light beams to fix at a desired spot size on the
surface of the wafer 110.~~

30 As illustrated in FIG. 1, the stationary laser beam
intercepts the wafer surface at normal incidence. After the
split beam contacts the wafer surface it is reflected back
through the components shown, particularly onto third mirror
element 109, second mirror element 108, optics arrangement
107, DIC prism 106, polarizing beamsplitter 105, half wave

plate 104, first mirror element 103, and optical isolator 102. Again, two beams illuminate the wafer surface, and two beams are thus returned to third mirror element 109, second mirror element 108, optics arrangement 107, and to DIC prism 106.

5 DIC prism 106 combines the two retro beams into a single beam, which is returned through the remaining elements illustrated and toward laser 101. The optical isolator 102 attenuates the beam significantly by orthogonal polarization rejection at polarizers 120 and 118, respectively.

10 *See B1* ~~While the system disclosed herein illustrates a normal application of a beam to the specimen 110, it is to be understood that the teachings of the current invention contemplate application of a beam to a specimen in non-normal or oblique angles. As used herein, the term "retro" or "retro beam" is intended to cover both normal and non-normal reflection of the beam from the specimen.~~

5
20 Portions of the current system resemble the system disclosed in pending U.S. Patent Application 08/933,771 to Mehdi Vaez-Iravani et al., filed September 19, 1997 and assigned to KLA-Tencor Corporation, the entirety of which is incorporated herein by reference.

25 In the configuration illustrated for the invention disclosed herein, two spot sizes have been successfully employed to perform the tasks described herein. One spot size is a 22 micron by 50 micron spot, while the other is a 22 micron by 340 micron spot. The spot size used is selected by using either lens 113 or lens 114. As may be appreciated by those of skill in the art, the larger spot size provides a higher throughput but has a tendency to produce lower quality scans, as lower power applied to the surface of the wafer yields less sensitivity. As disclosed herein, various spot sizes may be employed successfully with this invention, including the two disclosed herein, while still within the scope of the invention. Generally speaking, a larger spot

30

size will yield less sensitivity and greater throughput while a smaller spot size will produce greater sensitivity but take longer to complete a scan.

5 The retro beam will, with ideal optical alignment, return along the same path as the incident beam if and only if the surface is normal to the beam. With this knowledge, a measurement device or sensor can be located within the path illustrated in FIG. 1 to measure deviation of the retro beam from the transmitted beam.

10 The current system provides the ability to perform a deviation measurement using the bright field scanning Nomarski Differential Interference Contrast sensor 106. The bright field scanning Nomarski Differential Interference Contrast sensor 106 splits the beam into two separate beams which are applied to the surface of the specimen 110 as shown in FIGS. 1 and 2 and outlined above. The specimen 110 is rotated about a vertical axis and concurrently translated horizontally during a typical scan while the beam remains stationary. As a result of the scanning process, the Nomarski DIC sensor 106 senses occurrences in a predetermined direction, such as in a tangential direction from the center of the specimen, while the optical lever created by the optics senses occurrences in an orthogonal direction to that of the Nomarski DIC sensor 106. While the system may use the Nomarski DIC sensor 106 to measure in the tangential direction and the optical lever to measure in the radial direction, it is to be understood that other orientations are possible but it is preferred that the Nomarski DIC sensor and optical lever are always orthogonal to one another.

30 FIG. 1 illustrates one embodiment of the system with a diode/detector array 117 receiving the retro beam from the isolator's input polarizer 118. While the diode/detector array, as will be described below, is preferably a multiple element array of detector-diodes, the system could be

implemented alternately using a CCD sensor, which has certain drawbacks. The system illustrated in FIG. 2 presents an alternate positioning of the diode/detector array 117. The diode/detector array 117 in FIG. 1 is positioned proximate the optical isolator 102 to divert the retro beam using input polarizer 118. Alternately, the diode detector/array 117 may be positioned just before the DIC prism in the incident path such that the polarizing beamsplitter 105 diverts the retro beam toward the detector array, as illustrated in FIG. 2. In either condition, the retro beam is deflected from the path toward the diode/detector array, and any deviation from normal constitutes a local wafer surface irregularity. The beam wander results in the retro beam illuminating different diodes in the array, discussed below. Weighting the signal from each detector with a weight proportional to the relative position of the beam and adding signals from all detectors in conjunction with a signal normalization using the total detected light power provides a linear voltage proportional to the beam position independent of the absolute light power level. The system measures the summed diode signal and at the same time records the (x,y) or (r, θ) position on the wafer and generates a map of relative surface slopes. The integrated signal of the slope map produces a surface topography or surface height map.

A sample detector array having a beam imparted thereon is illustrated in FIG. 3. The diode/detector array 117 is made up of 76 adjacent detector elements each having the ability to have electrical connections at exposed ends of the element. Different sized arrays may be employed while still within the scope of the current invention; however, as discussed below, large two-dimensional blocks of detectors have speed and size/sensitivity concerns which are undesirable. The overall diode/detector array 117 includes 76 diodes, each diode having a 280 micrometer length with 30 micrometers between elements.

The entire mechanical dynamic range of the array in this longest direction is 23.56 millimeters. The width of these elements is 6.35 millimeters, and thus mechanical alignment is non-critical for a one millimeter diameter beam.

5 According to the arrangement presented in FIGs. 1 and 2 in conjunction with the diode/detector array 117 illustrated, the system measures output from each of the 76 elements in the array and calculates the center of mass for the entire arrangement, normalized with the total detected light power.

10 From FIG. 3, the beam is nominally positioned at a predetermined location in the retro beam path when the system according to FIGs. 1 or 2 is operating. The relative power of the beam is Gaussian, as shown in FIG. 4. The arrays are preferably sized such that the expected beamwidth spans several array elements, and as shown in FIG. 3, the beam spans
15 six elements of the array. The arrangement shown preserves the sensitivity of the system over a larger mechanical dynamic range than, for example, a bi-cell wherein the beam strikes two cells in the two cell array. The system operates by
20 scanning the wafer and monitoring the movement of the retro beam from the nominal value in the sensor array arrangement shown in FIG. 3. Typical beam deflection in the FIG. 3 arrangement is right to left, meaning that the beam will typically travel right or left in the presence of anomalies on
25 the wafer surface.

Each diode detector in the 76 element diode/detector array 117 operates with a pre-amplifier as shown in FIG. 5. The pre-amplifier is configured as a conventional trans-conductance amplifier having low pass filtering. Amplifier
30 501 has resistor 502 and capacitor 503 connected in parallel therewith in a feedback orientation. Diode 504 represents one of the 76 diodes in the array. Each diode, such as diode 504 of FIG. 5, operates in a photo-conductive mode, or in other words operates with a bias voltage. The feedback resistor 502

determines the gain of the amplifier, while the resistor and the capacitor act as a single pole low pass filter having a time constant equal to RC . This provides a -3 dB cutoff frequency.

5 In order to preserve sensitivity for the arrangement shown, the pre-amplifier gain must be relatively high. High preamplifier gain results in an increased position signal which can be too large for an analog to digital converter. Thus the configuration shown requires a scheme to increase the
10 mechanical dynamic range while preserving sensitivity, which can be on the order of less than .000001 rad for the system illustrated.

05 15 The signals from each individual diode are summed as shown in FIG. 6 using a conventional inverting sum amplifier. From FIG. 6, the weighted summing amplifier includes amplifier 601, parallel feedback resistor 602, and parallel capacitor 603. Weighting resistors 611, individually denoted 1 through
20 n , are of resistances R , $3R$, through $[(2n)-1] * R$, thereby providing weighting of the signals received from the sensor array. Weighting provides a skewing of information based on the position of the beam; for a beam which is further away than expected, the signal returned from the arrangement of FIG. 6 and subsequent drawings is larger than that of a beam which is only slightly off center. One summing amplifier is
25 used for each group of amplifiers as shown in FIG. 7, wherein each group has five amplifiers and accordingly five array elements. The optimal number of diodes to be grouped together depends on the laser beam width, diode size, and the gap between the diodes. The system determines the position signal
30 by subtracting the values from two neighbor groups of diodes from one another; for example, from FIG. 7, each element in the array has a diode associated therewith along with a preamplifier in accordance with FIG. 5. Each preamplifier has a weight associated therewith, and as shown in FIG. 7, the

center elements are numbered 1 and 2, are each attached to preamplifiers, and are weighted with a value of 1. The outermost elements are numbered 9 and 10 and have diodes associated therewith, as well as preamplifiers as in FIG. 5. The outermost elements have weights of 9 associated therewith. Thus the summing amplifiers 701 and 702 receive the weighted signals and compare them in summation element 703. The result of this comparison is the position signal for this diode group of 10 diodes, which is then compared with position signals from other groups of 10 diodes.

The center group illustrated in FIG. 7 outputs a signal relative to the beam offset as shown in FIG. 8. Nominal beam offset provides a minimal return, out to an approximately 1200 micrometer offset which produces a relative return of ± 1.0 .

FIG. 9 illustrates the stair-stepping arrangement of weightings used in accordance with the current invention for the 76 diode/array element arrangement of FIG. 3. As shown herein, 20 of the 76 diodes or array elements of the diode/detector array 117 each are connected to resistors, or weighting elements, which provide weighting according to relative position. For example, diode/array element 1 is multiplied by 9 in weighting resistor group 901 and also by 1 in weighting resistor group 904. Diode/array element 2 is multiplied by 9 in weighting resistor group 902 as well as by 1 in weighting resistor group 904. This stair-stepping dual-weighting arrangement permits a relatively linear response across the diode/detector array 117 by essentially mixing weights of adjacent resistors and not overweighting or underweighting areas of the diode/detector array 117, while concurrently providing significant signal deviation upon slight beam movement. The arrangement shown prevents saturation of the signal and preserves the dynamic range over the expected path of the retro beam. From FIG. 9, elements 1, 3, 5, 7, . . . 19 are weighted in weighting resistor group

901, with elements 9 and 11 each receiving weight 1 and elements 1 and 19 receiving weight 9. These elements are summed in position signal group 3 summing element 906. Simultaneously, elements 1, 3, 5, 7, and 9 are weighted with elements 2, 4, 6, 8, and 10 in weighting resistor group 904, thereby avoiding overweighting of element 1 or underweighting of element 9. The ten elements 1 through 10 are summed in position signal group 1 summing element 907. All position signal groups provide information to position signal selector 1001, which converts the information into a position signal.

As may be appreciated from a review of the stair-stepping arrangement of FIG. 9, the ends of the 76 element array will each have a lone grouping of 5 elements and 5 weights which will normally not be summed with other elements. Various options are available in this edge condition. First, the second set of weighting elements may be omitted and the signal from the pertinent five elements only summed with one position signal group rather than the two used for all other diode/detector elements. Alternately, the two groups of five leftover elements may be compared to one another, but this is less desirable. It is recommended that the edge elements simply be weighted and summed using only a single weighting element, rather than the two weighting elements used by the non-edge groups of diode/detector elements.

FIG. 10 illustrates passing of data from the various signal groups 1 through n to a multiplexer 1003, which receives a digital signal from programmable array logic (PAL) 1002. From FIG. 10, the system generates a group total detector power for each group in addition to the signal. The power of each group is compared to a given power threshold, and based on the output of these comparisons, the system uses the PAL 1002 to decide which group should be made active. In other words, the PAL determines which group has exceeded the required threshold, passes that group number to the

5 multiplexer 1003, and the multiplexer 1003 only passes the desired group as output. At any given moment, only the group of detectors containing the most power are passed to the system and are used to determine position. The arrangement shown eliminates the electronic and detector noise associated with detectors not containing any signal.

10 The resultant system provides resolution for various types of anomalies on the wafer surface. Whereas conventional flatness tools had the ability to address problems with bowing/warping, site flatness or thickness variations, and polishing dimples by evaluating relatively large height errors coupled with relatively large lateral dimensions, such tools did not have the ability to detect small height differences and small diameter defects, which required a conventional defect tool. The conventional defect tool could detect particles, scratches, haze, microroughness, and other miscellaneous small extent defects. Certain undesirable surface features had been undetectable using either conventional flatness tools or defect tools, particularly in situations involving device geometries for which relative surface height variations of 100 nanometers or less are significant. The current system provides the ability to address these mid-range concerns, and scanning using the current system takes on the order of minutes rather than several hours to complete.

20 While the invention has been described in connection with specific embodiments thereof, it will be understood that the invention is capable of further modifications. This application is intended to cover any variations, uses or adaptations of the invention following, in general, the principles of the invention, and including such departures from the present disclosure as come within known and customary practice within the art to which the invention pertains.